

VERTICAL DISTRIBUTION OF GALACTIC DISC STARS AND GAS CONSTRAINED BY A MOLECULAR CLOUD COMPLEX

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ABSTRACT

We investigate the dynamical effects of a molecular cloud complex with a mass $\sim 10^7 M_\odot$ and a size \sim a few 100 pc, on the vertical distribution of stars and atomic hydrogen gas in a spiral galactic disc. Such massive complexes have now been observed in a number of spiral galaxies. The extended mass distribution in a complex, with an average mass density *six times higher* than the Oort limit, is shown to *dominate* the local gravitational field. This results in a significant re-distribution or clustering of the surrounding disc components towards the mid-plane, with a resulting decrease in their vertical scale-heights.

The modified, self-consistent stellar density distribution is obtained by solving the combined Poisson equation and the force equation along the z-direction for an isothermal stellar disc on which the complex is imposed. The effect of the complex is strongest at its centre, where the stellar mid-plane density increases by a factor of 2.6 and the vertical scale-height decreases by a factor of 3.4 compared to the undisturbed stellar disc. A surprising result is the large radial distance ~ 500 pc from the complex centre over which the complex influences the disc, this is due to the extended mass distribution in a complex. The complex has a comparable effect on the vertical distribution of the atomic hydrogen gas in the galactic disc. This ‘pinching’ or constraining effect should be detectable in the nearby spiral galaxies, as for example has been done for NGC 2403 (Sicking 1997). Thus, the gravitational field of a complex results in local corrugations of the stellar and HI vertical scale-heights, and the galactic disc potential is highly non-uniform on scales of the inter-complex separation of ~ 1 kpc.

Running Title: Vertical constraining by a cloud complex

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1. INTRODUCTION

It is well known that the interstellar molecular hydrogen gas in the Milky Way galaxy is contained in giant molecular clouds, with a typical radius of 20 pc and a mass of $\sim 5 \times 10^5 M_\odot$ each (Scoville & Sanders 1987). It is also established that the giant molecular clouds are further segregated in larger features which have been variously called as complexes or clusters or chains (Sanders et al. 1985, Rivolo, Solomon, & Sanders 1986, Dame et al. 1987). These complexes are large, well-defined, discrete objects as seen by the closed contours of the CO distribution. Such a hierarchical distribution in complexes or associations has also now been observed in external galaxies such as M 51 (Lo et al. 1987, Rand & Kulkarni 1990), M 83 (Lord & Kenney 1991), and M 100 (Rand 1995), see Section 2 for details. The typical molecular cloud complex has a mass of $\sim 10^7 M_\odot$ and a size of \sim a few 100 pc, and a central total scale-height of about 120 pc. Thus, the mass distribution in a complex is elongated and it has an oblate spheroidal shape.

The average observed number density of hydrogen molecules in a typical complex is about 16 cm^{-3} , which equals $1 M_\odot \text{ pc}^{-3}$. We note that this is about *six times higher* than the dynamical or total mass density in the mid-plane of the galactic disc in the solar neighbourhood as given by the Oort limit of $0.15 M_\odot \text{ pc}^{-3}$. (Oort 1960, Binney & Tremaine 1987). This ratio may be even higher than six since the recent estimates based on the Hipparcos data (e.g., Binney 1997) give a smaller value of $0.076 M_\odot \text{ pc}^{-3}$ for the Oort limit. Therefore, such a massive, extended mass distribution in the form of a molecular cloud complex in a galactic disc would *dominate* the local gravitational field. Thus the stars and the atomic hydrogen gas in the surrounding galactic disc would respond to the additional and dominant gravitational field due to the complex, and tend to get clustered towards the mid-plane, with a resulting decrease in their vertical scale-heights. We investigate this effect quantitatively, and show that the above intuitive picture is confirmed by our calculations.

A similar clustering effect will also be seen around an individual giant molecular cloud, though with a much smaller magnitude and over a smaller spatial range than for the case of a complex.

We show that the gravitational field of a complex results in a local variation of the stellar and HI vertical scale-heights, and the net disc potential is locally non-uniform. This would be of interest in the general theoretical studies of galactic disc dynamics since the usual assumption of uniform and smooth mass distribution or potential is shown to no longer hold good.

A similar problem involving the effect of dark halo on the vertical distribution of the embedded disc matter was studied by Bahcall (1984). However, in that case the halo acts as a perturbation in the plane and hence a perturbation analysis was used. In our work, on the other hand, the complex dominates the gravitational field in the disc region around it.

In another analogous problem, a planar disc response to the perturbation due to an imposed massive cloud taken to be a point mass was treated by Julian & Toomre (1966), whereas we have treated the effect on the vertical disc distribution due to a spatially extended mass distribution in a complex which dominates the local gravitational field. Further, we argue that the complex has a stronger effect on the vertical than the planar disc distribution (Section 5).

In Section 2, the observed physical parameters for the typical giant molecular cloud complex, and also the choice of the galactic disc potential used are described. The formulation of the equations for the self-consistent response of a disc to the imposed complex are given in Section 3. The results on the vertical constraining effects of a complex on stars and HI gas and a comparison with observational data are given in Section 4. A discussion of a few general points are given in Section 5, and Section 6 contains a brief summary of our conclusions.

2. PARAMETERS FOR COMPLEX AND GALACTIC DISC

2.1 Parameters for a cloud complex

Observations of a number of spiral galaxies have now clearly established the existence of giant molecular cloud complexes or associations in our Galaxy (see §1), and also in external galaxies: for example as in M51 (Lo et al. 1987, Rand & Kulkarni 1990), M83 (Lord & Kenney 1991), M 31 (Allen & Lequex 1993), SMC (Rubio, Lequex, & Boulanger 1993), M100 (Rand 1995), NGC 4414 (Sakamoto 1996), NGC 5055 (Thornley & Mundy 1997), M81 (Brouillet et al. 1998), and for the central regions of 20 nearby spiral galaxies (Sakamoto et al. 1999) - some of which overlap with the galaxies listed above. Thus, such large gas features appear to be common in spiral galaxies.

The molecular cloud complexes in these galaxies are observed to cover a wide range of masses from 10^6 to $10^8 M_\odot$, with a *typical mass* of $10^7 M_\odot$ and a *typical size* of a few hundred pc. These complexes are shown to be spatially coherent features (Rivolo et al. 1986), and are statistically significant and are not mere superpositions or artifacts of the low spatial resolution of the observations (Rivolo et al. 1986, Rand & Kulkarni 1990, Sakamoto 1996).

Gravitationally bound complexes with the above typical values are shown to occur naturally via induced gas instabilities in a gravitationally coupled star-gas two-fluid galactic disc (Jog & Solomon 1984). From the observed star complexes, Efremov (1995) has argued that gas ‘superclouds’ of $\sim 10^7 M_\odot$ occur in all spiral galaxies. Rand & Kulkarni (1990) show for M 51 that features above a few times $10^7 M_\odot$ may not be gravitationally bound. Hence for our work, we use a typical complex of mass equal to $10^7 M_\odot$ and a radius of 200 pc. We assume a maximum height at the centre of the complex to be equal to 120 pc which is the FWHM as observed for the molecular gas in the galactic disc (Sanders, Solomon, & Scoville

1984, Clemens et al. 1986). Further, the mass distribution inside a complex is assumed to be uniform for simplicity. This gives a mean molecular hydrogen gas density, n , in a typical complex to be equal to $15.8 \text{ H}_2\text{cm}^{-3}$. The mass density in a complex, ρ_{complex} , assuming a 10 % gas number fraction in helium, is equal to $2.8m_H n$ where m_H is the atomic mass of hydrogen. For the typical complex, ρ_{complex} is equal to $1 \text{ M}_\odot\text{pc}^{-3}$.

This is a conservative choice because a complex more massive than this will have a stronger effect on the stars but since it is not bound the effect will be short-lived, hence we do not consider complexes more massive than 10^7 M_\odot . Also for these more massive and extended complexes, the effect of the differential rotation in the disc cannot be neglected.

It has been claimed by some authors that the molecular gas distribution is hierarchical and may be denoted as a fractal, however this covers largest entities of sizes $\sim 100 \text{ pc}$ which are self-gravitating (Falgarone, Phillips, & Walker 1991). The fractal description therefore does not seem to cover the larger size bound complexes that are observed in a number of galaxies.

The complex is taken to be co-planar with the galactic disc, and z is along normal to the galactic plane, with $z = 0$ denoting the galactic mid-plane. The radial distance r is measured from the complex centre, taken to be at $r = 0$. Here r and z are the cylindrical polar co-ordinates. The mass distribution in a cloud complex is that of an oblate spheroid, and the force per unit mass due to it along z is taken from Schmidt (1956) who had obtained it in the context of galaxy mass models:

$$(K_z)_{\text{complex}} = 4\pi G \rho_{\text{complex}} \epsilon^{-3} (1 - \epsilon^2)^{1/2} z (\tan \beta - \beta) \quad (1)$$

where β is given within and outside the ellipsoid respectively by:

$$\sin\beta = \epsilon \quad (2)$$

$$r^2 \sin^2 \beta + z^2 \tan^2 \beta = a^2 \epsilon^2. \quad (3)$$

Here ϵ is the eccentricity of the oblate spheroid and is equal to $\epsilon = (1 - c^2/a^2)^{1/2}$ where c and a are the semi-minor and semi-major axes along the z and the radial directions respectively. For a typical complex, $c = 60$ pc and $a = 200$ pc as discussed above, so that $\epsilon = 0.95$.

2.2 Parameters for the galactic disc

We have assumed the galactic disc to consist of a single isothermal stellar component with the density distribution along z satisfying the *sech*² law (Spitzer 1942), rather than assuming a more realistic, multi-component galactic mass model say by Carlberg & Innanen (1981). This was done for simplicity since it captures the main z distribution of the galactic disc, and because it allows us to clearly illustrate the physical effect of the imposed complex on the stellar disc.

Further we assume for simplicity that the stellar distribution remains isothermal even in presence of a complex, with the z -velocity dispersion, $\langle (v_z)_s^2 \rangle^{1/2}$, the same as observed in the undisturbed disc, namely 15 km s⁻¹ (Binney & Merrifield 1998). For an isothermal, one-component, self-gravitating stellar disc, the density distribution, ρ_s , and the force per unit mass, $(K_z)_s$, are obtained by solving the force equation along z along with the Poisson equation (Spitzer 1942, Rohlfs 1977) and are given respectively by:

$$\rho_s = \frac{\langle (v_z)_s^2 \rangle}{2\pi G z_0^2} \operatorname{sech}^2 \left(\frac{z}{z_0} \right) \quad (4)$$

$$(K_z)_s = \frac{-2 \langle (v_z)_s^2 \rangle}{z_0} \tanh \frac{z}{z_0} \quad (5)$$

where

$$z_0 = \left[\frac{\langle (v_z)_s^2 \rangle}{2\pi G \rho_0} \right]^{1/2} \quad (6)$$

here z_0 is taken to be a measure of the thickness of the undisturbed disc but is not identically equal to the vertical scale-height $h_{1/2}$ (or HWHM) which we will use in Section 4 and later sections. For small z/z_0 , the density distribution is that of a gaussian.

To get a quantitative feel for the effect of the complex, in Fig. 1 we plot the magnitude of the z -force per unit mass due to a complex (eq.[1]) and that due to the undisturbed stellar disc without the complex (eq.[5]) versus z at the complex centre ($r = 0$). It is interesting that upto $z \leq 200$ pc, the force due to the complex dominates over that due to the disc. This ratio is a maximum, equal to 9.5, at the outer edge of the complex, where the force due to the complex is a maximum. Because of the large value of this ratio, we are justified in assuming that the complex itself is not affected by the stellar disc.

Fig. 2 shows the ratio of the force per unit mass along the z direction due to the complex to that due to the undisturbed stellar disc versus z at different radial distances from the centre of the complex. The ratio is large ~ 9.5 at the mid-plane over $r = 0$ to $r = 200$ pc and decreases gradually with the radial and vertical distance, and indicates the large spatial range over which the complex affects the disc. This large range is confirmed for the self-consistent disc response in Section 4.

3. FORMULATION OF EQUATIONS

We first formulate the equations for the self-consistent response of the stellar

disc to the imposed complex potential and obtain the modified stellar density distribution.

3.1 Effect on Stars

We obtain the density distribution along the z direction at a given radial distance, r , from the centre of the complex, so that we look at the distribution along a normal cut across a complex. The equations to be solved to study the modified stellar mass density distribution, ρ_s , in the presence of an imposed cloud complex are the force equation along the z direction and the joint Poisson equation for the stars and the complex :

$$\frac{\langle (v_z)_s^2 \rangle}{\rho_s} \frac{d\rho_s}{dz} = (K_z)_s + (K_z)_{complex} \quad (7)$$

and,

$$\frac{d(K_z)_s}{dz} + \frac{d(K_z)_{complex}}{dz} + \frac{d(K_r)_{complex}}{dr} + \frac{(K_r)_{complex}}{r} = -4\pi G(\rho_s + \rho_{complex}) \quad (8)$$

where $(K_z)_s$ and $(K_z)_{complex}$ are the z -components of the force per unit mass due to the modified stellar distribution and the complex respectively, and $(K_r)_{complex}$ is the r component of the force per unit mass due to the complex. Since the stellar disc is thin compared to its radial extent, only the z component of the Laplacian for the stars needs to be retained on the l.h.s. of the Poisson equation, as usual (see e.g. Binney & Tremaine 1987, pg. 199). For the complex, on the other hand, both z and r terms are required since the z and r dimensions are comparable. Because of the azimuthal symmetry w.r.t. the complex centre, the ϕ term for both stars and the complex is zero.

The complex is assumed to be unaffected by the disc (Section 2.2), hence the joint Poisson equation (eq.[8]) effectively reduces to that for the re-distributed stellar

case alone. Thus, on combining the above two coupled first-order linear differential equations in ρ_s and $(K_z)_s$ (eq.[7]-[8]), we get the following linear, second-order differential equation in ρ_s :

$$\frac{d}{dz} \left(\frac{\langle (v_z)_s^2 \rangle}{\rho_s} \frac{d\rho_s}{dz} \right) = -4\pi G\rho_s + \frac{d(K_z)_{complex}}{dz} \quad (9)$$

where the term due to the complex on the r.h.s. of equation (9) is obtained starting from equation (1).

The above formulation effectively assumes the complex to be stationary in the disc and long-lived. This is justified since the response time of a star given by $2\pi/\nu = 6 \times 10^7$ yr, where ν is the vertical frequency (Binney & Tremaine 1987), is comparable to the crossing time of the complex in the plane, and it is smaller than the life-time of the complex which is gravitationally bound.

3.2 Effect on Atomic Hydrogen Gas

We next consider the effect of a molecular cloud complex and the modified stellar distribution on the atomic hydrogen gas in a galactic disc, also taking account of the self-gravity of the atomic gas. The atomic hydrogen gas is assumed to be isothermal as is known from gas dynamics, with the z-velocity dispersion, $\langle (v_z)_g^2 \rangle^{1/2} = 8$ km s⁻¹ (Spitzer 1978). The modified distribution of the gas is given by:

$$\frac{d}{dz} \left(\frac{\langle (v_z)_g^2 \rangle}{\rho_g} \frac{d\rho_g}{dz} \right) = -4\pi G\rho_s - 4\pi G\rho_g + \frac{d(K_z)_{complex}}{dz} \quad (10)$$

where ρ_s denotes the re-distributed stellar density obtained from equation (9). The gas has a negligible effect on stars in the presence of a complex, hence we do not include it in the study of stellar distribution in Section 3.1.

4. RESULTS

4.1 Effect on Stars

First, we consider the effect of a molecular cloud complex on stars, and obtain the modified stellar density distribution. The problem studied in the present paper is analogous to that of the re-distribution of charges in the presence of an external imposed electric field, that is commonly studied in the electromagnetic theory (e.g., Jackson 1976). This analogy was first sought to help solve equation (9) by assuming that the stellar distribution reverts back to the undisturbed value at large z . However, we find that even if we start at very large z values of ~ 2 kpc, the disc still retains the memory of the initial solution, and hence one cannot exploit this analogy to solve this problem. This is because while 2 kpc is a large distance physically for the disc being studied, mathematically it is still not large enough for this approach to work.

Instead, the second-order, linear differential equation in ρ_s (eq. [9]) is solved as an initial value problem from inside-out numerically using the fourth-order Runge-Kutta method (Press et al. 1986). The initial condition of $d\rho_s/dz = 0$ at $z = 0$ is used since that would be true for any realistic mass distribution in a disc. The value of the re-distributed density ρ_s at the mid-plane ($z = 0$) is not known a priori. We constrain this by assuming that the total column density of the undisturbed stellar disc, Σ_s , remains constant even in the presence of a complex. Thus, the complex is assumed to re-distribute the stars only along z at a given radius, and thus we have solved this 1-D problem. The radial force due to a complex can be neglected as discussed in Section 5.

The complex centre is taken to be located at the galactocentric radius of 8.5 kpc, in the solar neighbourhood. Here, the unperturbed central, mid-plane stellar density is known from observations to be $0.07 M_\odot \text{ pc}^{-3}$ (Binney & Tremaine 1987). The equation (9) with zero contribution from the complex is solved and this gives the variation with z in the self-gravitating, undisturbed stellar mass density (Fig. 3, dashed line). This shows a $\text{sech}^2 z$ distribution as expected for an undisturbed

disc (eq.[4]). The net column or surface density for stars, Σ_s , at a given radius is obtained by summing up the area under the curve and doubling it and this is found to be $47.6 M_\odot \text{ pc}^{-2}$. Assuming the stellar surface density at a given radius to remain constant when the complex is imposed, equation (9) is solved to obtain the modified or re-distributed stellar density distribution, which is also shown in Fig. 3 (solid line). *The complex strongly alters the vertical distribution of the stellar disc.* First, the central stellar density at $z = 0$ increases by a factor of 2.6 to be equal to $0.19 M_\odot \text{ pc}^{-3}$. Second, the vertical distribution still satisfies a *sech*² law but now the scale-height $h_{1/2}$ (HWHM) of the distribution has decreased by a factor of 3.4 to be equal to 88 pc. This ‘pinching’ or constraining effect confirms the intuitive picture given in Section 1.

This procedure is repeated at different radii from the complex centre to get the net 2-D re-distribution of the stars, where the constant net stellar column density of $47.6 M_\odot \text{ pc}^{-2}$ is used as explained above. In Fig. 4, the resulting modified vertical scale-height, $h_{1/2}$, is plotted as a function of radial distance from the complex centre (solid line). Also shown is the constant undisturbed scale-height (dashed line). The most striking result is the large radial distance from the complex centre over which the complex influences the stellar distribution. This interesting and somewhat unexpected result is due to the extended mass distribution in a complex. The trough representing the scale-height is broad so that even at a radial distance of 500 pc from the complex centre, the vertical scale-height decrease is still 8%. The scale-height asymptotically reverts back to the undisturbed value of 299 pc only beyond $r = 1$ kpc. The broad trough makes it more likely that this effect would be detected in observations (see Section 4.4). Thus, the resulting stellar scale-height distribution is locally corrugated, see Section 4.4 for a comparison with observations.

In Fig. 5, we show a contour diagram for the iso-density contours of the modified stellar distribution to show another aspect of the constraining effect due to the

complex. In the presence of a complex, a higher range of density values is covered over a smaller z -range than for the undisturbed disc. As in the variation of scale-height (Fig. 4), the density also asymptotically reverts back to the undisturbed value of $0.035 M_{\odot} \text{ pc}^{-3}$ at the scale-height = 299 pc, only beyond $r = 1$ kpc, as expected since the scale-height and density variations are inter-related. An interesting point is that the density contours are clearly curved around the complex, thus highlighting the important effect of the complex in re-distributing the stellar matter around it.

4.2 Effect on stars: Parameter Study

We study the effect of a complex over the parameter space covering a wide range of realistic values for the complexes and the stellar disc density. The results from this study are given in Table 1. Columns 2-4 give the input parameters for the complex, namely the semi-major axis a , the semi-minor axis c , and the molecular hydrogen number density n . Column 5 gives the total stellar disc surface density Σ_s . Columns 6 and 7 give the resulting mid-plane density and the vertical scale-height $h_{1/2}$ for the modified stellar distribution.

Case 1 is the typical case studied in Section 4.1 (Fig. 4), which is used as a benchmark with which we compare the results from the other cases. Case 2 with double the total disc surface density of case 1 represents the peak of the molecular ring region at 6 kpc. This follows from the radial dependence of surface density for an exponential disc ($\propto \exp[-r/r_{exp}]$) with a disc scale-length, r_{exp} , of 3.5 kpc as in the Galaxy (Binney & Tremaine 1987). Here the unperturbed central density is $0.28 M_{\odot} \text{ pc}^{-3}$ and the scale-height is 150 pc as obtained by solving equation (9) with zero contribution from the complex. The effect of a complex is smaller in this case, with the mid-plane density increasing and the scale-height decreasing only by a factor of 2 - see the last two columns, case 2 in Table 1. The trough showing the effect of a complex is shallower and less broad in this case because a higher density disc is less disturbed by the same complex.

The converse result would be seen for a lower stellar disc surface density where the effect of a complex would be stronger. This could be applicable for the few, less-massive cloud complexes observed in the outer Galaxy (Digel, Thaddeus, & Bally 1990).

A smaller value of the complex number density of $10 \text{ } H_2 \text{ cm}^{-3}$ results in a smaller increase in the mid-plane density to $0.14 \text{ } M_\odot \text{ pc}^{-3}$ at $r = 0$, and a larger central scale-height of 119 pc, as expected because the trough in the scale-height is shallower (case 3). A complex with a smaller radius a (case 4), or with a smaller height c (case 5), with the same density as in case 1, also results in an effect of smaller magnitude as expected.

4.3 Effect on Atomic Hydrogen Gas

The modified HI distribution is obtained by solving equation (10) where ρ_s is obtained as a solution to equation (9) (see Section 3.2). The atomic hydrogen gas surface density is taken to be constant at $5 \text{ } M_\odot \text{ pc}^{-2}$ as observed in the inner disc (Scoville & Sanders 1987). This, plus the assumption of the gradient of the gas density to be zero at $z = 0$, as done before for the stellar case (Section 4.1), allows us to solve equation (10). The re-distributed gas density at the mid-plane at the central radius of the complex is higher by a factor of 3.2 and the vertical gas scale-height is lower by a factor of 3.3 compared to the case without the complex. Fig. 6 shows the vertical scale-height for HI as a function of radius. The vertical constraining of HI gas as a function of input parameters would show a trend similar to that for stars as studied in Section 4.2.

4.4 Comparison with Observations

1. *The ‘pinching’ or the constraining effect:* The ‘pinching’ or the constraining effect of a complex on the z -distribution of stars and gas (Sections 4.1 - 4.3) is strong in magnitude and it affects stars and gas upto a large radial distance of $\sim 500 \text{ pc}$

from the complex centre (Fig. 4). Nevertheless it could be missed unless it is looked for carefully. This is because in an edge-on galaxy like say NGC 891, the cumulative effect over many such complexes along a line-of-sight would average out and hence cannot be seen easily, and in a face-on galaxy the spatial z -distribution cannot be studied directly. Further, for the external galaxies, the uncertainty in the determination of the inclination angle and the ubiquitous presence of warps (Burton 1992) and also the flaring of gas can affect the determination of scale-height.

However, if one were to carefully analyze the information for the column density $N(l, b, v)$ where l, b, v are the galactic longitude, latitude and the line-of-sight velocity respectively, and model the data cube say as one does to study the spiral structure parameters, then in principle, the z scale-height variation predicted in our paper can be verified from observations for a nearby, inclined galaxy. This result for variation is in fact confirmed from the high-resolution HI mapping of NGC 2403 by Sicking (1997) who found that the vertical scale-height of HI shows variations on a scale of about 100 arc sec, which corresponds to about 1.3 kpc for the distance of 3.5 Mpc for this galaxy. This agrees with a total of ~ 1 kpc radial range affected by a complex as shown in our paper. Note that this is a late-type Sc galaxy with a large amount of molecular gas detected in it (Young et al. 1995).

For a more detailed spatial comparison, we need a resolution of about 2 arc sec corresponding to 100 pc at say a distance of 10 Mpc. The current HI surveys of galaxies are typically at 20 arc sec (e.g. Binney & Merrifield 1998, pg. 488). Thus only in our Galaxy the HI data have sufficient resolution to allow a more detailed study of the variation in scale-height due to a complex that we predict. We will attempt this in a future paper.

A recent, interesting paper has shown how the HI scale-height for face-on galaxies such as LMC may be determined using the technique of spectral correlation function (Padoan et al. 2001). Here the scale-height can be determined upto spatial scales

of the resolution for their data, namely, 20 pc. If this technique could be applied to HI data from other galaxies in which molecular cloud complexes have been observed (e.g., M 51, M 81), then it would give the variation in vertical scale-height around a complex. Note that since the effect of a complex is felt over 500 pc, and the above galaxies are a few Mpc away, the resolution required to study this variation is about 20 arc second which is exactly within the resolution of large-scale HI surveys of these galaxies.

Our paper also predicts the constraining effect for the old stars in the disc, which can be checked in the near-IR data on galaxies since that traces old stars. Unfortunately, in the literature on external galaxies, the data is averaged over radius to give only a typical vertical scale-length, as e.g. in the large sample of 486 galaxies studied by Ma et al. (1997). For our Galaxy also, the near-IR study by Freudenreich (1998) gives an average vertical scale-height, whereas the best fit to the near-IR data by Kent, Dame, & Fazio (1991) requires a constant scale-height upto a radius of 5 kpc and radially increasing beyond that. This agrees with the flaring behaviour expected if we take account of the average effect of the complexes in the inner Galaxy (see Section 4.4, point 2).

Thus, the observational verification of our results on the vertical constraining due to a complex is within the present observational capabilities, especially for a nearby, slightly tilted galaxy.

2. *Flaring of HI* : The molecular gas and hence the cloud complexes are located within the solar circle (Scoville & Sanders 1987). Thus the vertical constraining of the atomic hydrogen gas due to the molecular cloud complexes would abruptly stop at this radius and this could naturally explain the long-standing puzzle of why the atomic hydrogen gas shows flaring exactly outside of the solar position (e.g., Burton & te Lintel Hekkert 1986, Wouterloot et al. 1990). The details of this will be checked in a future paper that involves taking account of the effect of many such

complexes in the disc (also see Sections 4.5, and 5).

3. *Corrugation of the vertical scale-heights:* We have shown that a complex would result in the local corrugation of the vertical scale-heights of stars and gas. The previous studies of corrugation in the galactic disc typically refer to the variation in the mid-plane ($\langle z \rangle$) with radius of HI (e.g. Lockman 1977, Spicker & Feitzinger 1986), or the old stars (Florido et al. 1991), the physical origin of which is not yet understood, and we do not study it here. The stellar corrugation is color-dependent which Florido et al. (1991) attribute to star formation. We note that the local corrugation of the vertical scale-heights obtained in the present paper is an additional complexity, seen on top of the corrugation of the mid-plane, and has to be reckoned with while studying the z distribution in a spiral galactic disc. If the underlying molecular gas mid-plane is corrugated as it is in our Galaxy (Sanders et al. 1984), then the corrugation of scale-heights predicted here is a local phenomenon seen around a complex. It is probably easiest to detect this effect around a complex in nearby galaxies such as M 51 or M 81.

4.5 Implications for Galactic Dynamics

The massive, extended cloud complex and the resulting clustering of stellar disc mass around it means that the mass distribution and hence the potential of a galactic disc in a spiral galaxy is not uniform. The galactic disc potential is *non-uniform* on the scales of a typical observed separation between complexes ~ 1 kpc (Section 5). This could be important in the general theoretical studies of galactic disc dynamics in spiral galaxies. For example, this may contribute to the observed increase with age (Wielen 1977) of the stellar random velocity dispersion. The increase in stellar dispersion is a classic problem, and in the past it has been attributed as arising due to scattering of stars off molecular clouds (Spitzer & Schwarzschild 1951, Lacey 1984), or due to local spiral features (Barbanis & Woltjer 1967), or as a combination of both these processes (Jenkins 1992). The cloud complexes present a new source

of non-uniform potential on a spatial scale that lies between these two cases studied earlier. In a future paper, we will study the heating caused by the cloud complexes, and thus check the importance of the integrated dynamical effect of cloud complexes in a galactic disc.

The potential distribution resulting due to several such complexes would have the appearance of the "muffin-tin" potential that is used to study solids in condensed matter physics (e.g., Ashcroft & Mermin 1976). It would be very useful if future observations give the mass spectrum and the distances between such complexes in a spiral galaxy. This will decide if the influence of the various 'potential wells' located at the complex centres are distinct or they merge together (also see Section 5). This will be studied in the context of flaring in a future paper (see Section 4.4).

5. DISCUSSION

(1). The total molecular gas mass in the disc of our Galaxy is equal to $2 \times 10^9 M_\odot$, most of which is observed to be in the inner disc (Scoville & Sanders 1987). Assuming that all the molecular gas mass in the disc is in cloud complexes, there are about ~ 200 such complexes in the inner Galaxy and the typical separation between two neighbouring complexes can be calculated to be ~ 1 kpc. Since each complex can affect the distribution of stars and gas upto 500 pc and beyond from its centre on either side (see Figs. 4 and 6), hence the dynamical effect of the complexes taken together can effectively 'cover' or affect most of the disc. To address this question in detail, it would be necessary to have observational determination of the mass spectrum of the complexes, and the fraction of molecular hydrogen gas mass that exists in complexes in a galactic disc.

(2). We have assumed the net stellar disc column or surface density, Σ_s , at a given radius r to remain constant in the presence of a complex and have used this constraint to obtain the re-distributed stellar disc density (Section 4.1). The complex

will also exert a radial force on the surrounding disc components. However, the ratio of the radial to the z component of the force due to a complex is < 1 (Schmidt 1956), except near the mid-plane at the outer boundary of a complex. Further, from the radial force equation (e.g., Binney & Tremaine 1987), it can be shown that the ratio of the change in density along r to that along z will be proportional to the ratio of vertical to the radial mean square of the random velocity, which is observed to be $1/4$ (see Binney & Merrifield 1998, Chap. 10). Therefore, we can ignore the transfer or re-distribution of matter along the radial direction as compared to that along z , hence the assumption of constant surface density is valid.

(3). We have assumed for simplicity that the stellar disc surface density is constant across the complex. In a realistic galactic disc the mid-plane density increases at lower galactic radii. Hence the net effect of complex will be lower at the inner boundary of the complex than at the highest radius (see Section 4.2). For example, an exponential disc mass distribution with a scale-length of 3.5 kpc as observed for the Galaxy (Section 4.2), results in a 8% variation in the disc surface density between the inner and the outer edges of a complex. This results in a 7% difference in the scale-heights at the inner and outer boundaries of the complex. Thus the pinching effect would show a radial asymmetry, and the net scale-height distribution would be horn-shaped with the broad-end of the horn at a smaller radius.

6. CONCLUSIONS

We have studied the dynamical effects of a massive, extended giant molecular cloud complex, with a mass $\sim 10^7 M_\odot$ and a size \sim a few hundred pc, on the z -distribution of stars and atomic hydrogen gas in a spiral galactic disc. The main results obtained are:

(1). Physically, a superposition of a co-planar potential due to the complex on the stellar disc re-distributes the stars so that the stellar density at the mid-plane is

higher, and correspondingly, the scale-height of the stellar distribution is lower. The constraining effect of the complex is highest at its central radius, where the mid-plane stellar density is shown to increase by a factor of 2.6, and the vertical scale-height is shown to decrease by a factor of 3.4. The complex significantly affects the disc upto a large radial distance of 500 pc from its centre, and the undisturbed distribution is reached slowly beyond ~ 1 kpc. This is a direct consequence of the extended mass distribution in a complex. The complex is shown to have a comparable effect on the vertical distribution of the atomic hydrogen gas in the galactic disc.

(2). The verification of the ‘pinching’ or constraining effect predicted around a cloud complex is within the present observational capabilities, especially for a nearby, slightly tilted galaxy. In fact, this result has been confirmed from the observations of HI in NGC 2403 (Sicking 1997). Thus, the gravitational field of a complex results in local corrugations of the vertical scale-heights of the stellar and HI distributions in a galactic disc.

(3). The massive complex, and the resulting significant clustering of stellar mass around it, means that the gravitational potential in a typical spiral galactic disc is distinctly non-uniform on scales of the inter-complex separation of ~ 1 kpc. This would be of interest in the general theoretical studies of galactic disc dynamics since the usual assumption of a smooth and uniform disc potential is shown to be not valid.

(4). The observed onset of flaring of HI gas outside of the solar circle is probably due to the observed drop in the molecular gas content beyond this radius, where the vertical constraining due to the cloud complexes would not be operative. This will be studied in detail in a future paper.

(5). This paper has highlighted the importance of the dynamical effects of cloud complexes on a galactic disc. We stress that the complexes should be included as

a major structural component in the study of a spiral galaxy. Future observations that give the mass spectrum and distances between such complexes in a spiral galaxy are needed, these will help in deciding how far the effect of the nearby complexes overlaps.

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FIGURE LEGENDS

FIG. 1. — A plot of $|(K_z)_{complex}|$, the magnitude of the force per unit mass along z due to a complex and that due to the undisturbed stellar disc versus z , the distance from the mid-plane, at the complex centre. Upto $z \leq 200$ pc, the force due to the complex dominates over that due to the disc. The ratio is a maximum, equal to 9.5, at the outer edge of the complex ($z = 60$ pc).

FIG. 2. — A plot of $(K_z)_{complex}/(K_z)_s$, the ratio of the force due to the complex to that due to the undisturbed stellar disc, versus z at different radial distances from the complex centre, in steps of 50 pc. The curves for $r = 0, 200$, and 250 pc only are labeled for clarity. The ratio is large ~ 9.5 at the mid-plane over $r = 0$ to $r = 200$ pc and decreases gradually with the radial and vertical distance.

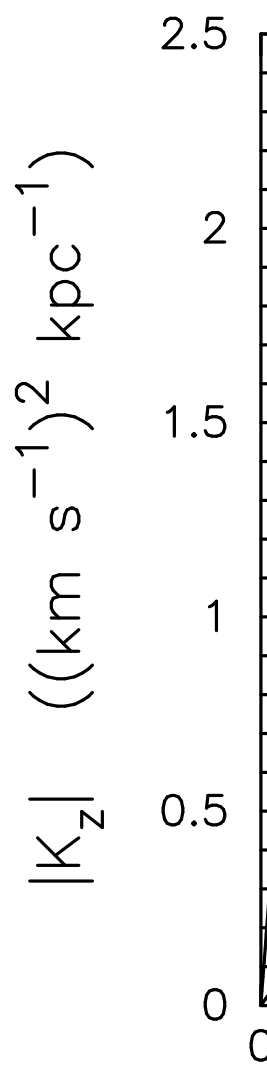
FIG. 3. — A plot of the modified stellar disc density in the presence of a cloud complex versus z , the distance from the mid-plane (solid line) at the centre of the complex, and also the self-gravitating, undisturbed stellar disc density without the complex (dashed line). The modified mid-plane density is 2.6 times higher and the vertical scale-height is smaller by a factor of 3.4 than the undisturbed case, showing the strong ‘pinching’ or constraining effect due to the complex.

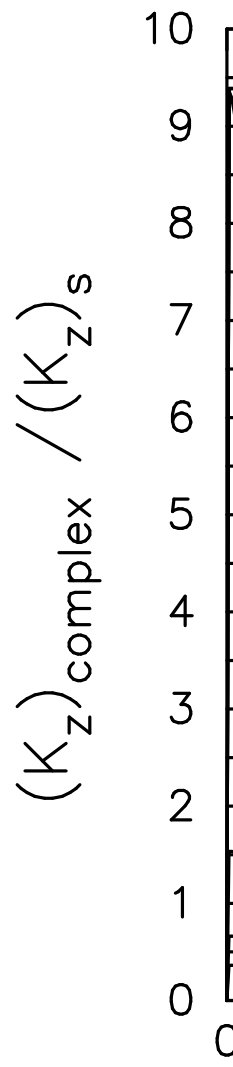
FIG. 4. — A plot of the vertical scale-height $h_{1/2}$ (HWHM) for the modified stellar distribution versus r , the radial distance from the complex centre (solid line), and the constant scale-height for the undisturbed stellar disc without the complex (dashed line). The vertical constraining by the complex is significant over a large radial distance ~ 500 pc from its centre, this is due to the extended mass distribution in a complex.

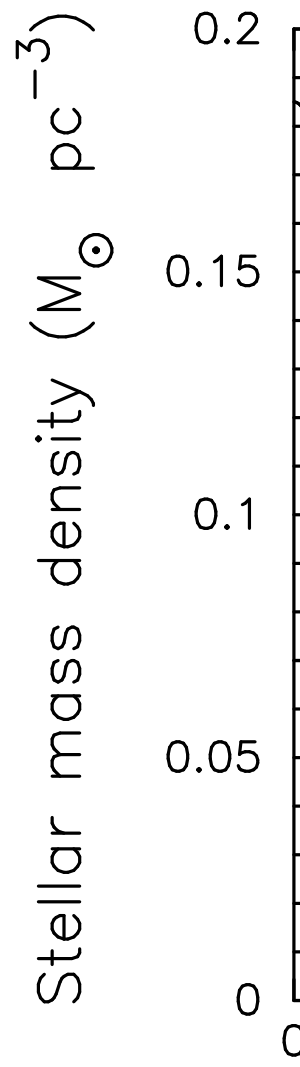
FIG. 5. — A contour diagram for the constant density contours of the modified stellar distribution in the r, z plane in units of $M_\odot pc^{-3}$. A higher range of stellar density values (upto $0.18 M_\odot pc^{-3}$) is covered over a smaller z -range than for the

undisturbed disc, this is due to the constraining effect of the complex. The contours are clearly curved around the complex, thus highlighting the important effect of the complex in re-distributing the stellar matter around it.

FIG. 6. — A plot of the vertical scale-height for the modified HI gas distribution versus r , the radial distance from the complex centre (solid line), and the constant gas scale-height for an undisturbed disc without the complex (dashed line). The constraining effect of the complex on the gas is similar to that for the stellar case (see Fig. 4).



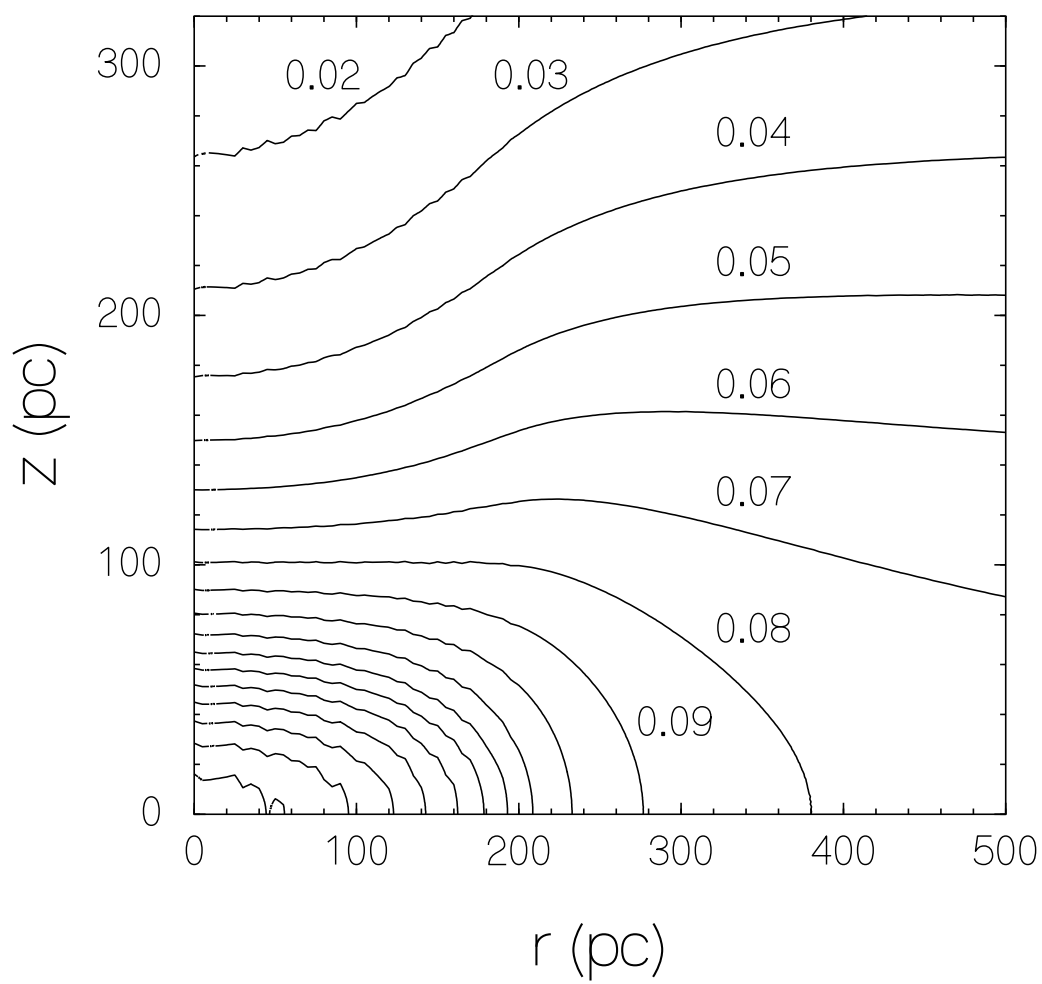




Vertical Scale—height (pc)

0
100
200
300

STELLAR DENSITY CONTOURS



Vertical Scale—height (pc)

160
140
120
100
80
60
40
20
0

Table 1: Effect of a cloud complex on stellar disc: Parameter Study.

Case	a (pc)	c (pc)	n (cm^{-3})	Σ_s ($M_\odot pc^{-2}$)	ρ_s ($M_\odot pc^{-3}$)	$h_{1/2}$ (pc)
1	200	60	15.8	47.6	0.19	88
2	200	60	15.8	95.1	0.53	71
3	200	60	10	47.6	0.14	119
4	150	60	15.8	47.6	0.17	97
5	200	45	15.8	47.6	0.17	96